# What are the joint models used in multibody kinematic optimisation for the estimation of human joint kinematics? a review

Dumas, Raphael; Andersen, Michael Skipper; Begon, Mickael

*Published in:*
Proceedings of the 4th International Digital Human Modeling Symposium

*Publication date:*
2016

*Document Version*
Accepted author manuscript, peer reviewed version

# What are the joint models used in multibody kinematic optimisation for the estimation of human joint kinematics? a review

R. DUMAS*†, M. S. ANDERSEN‡, M. BEGON\\

† *Université de Lyon, F-69622, Lyon, France; Université Claude Bernard Lyon 1, Villeurbanne; IFSTTAR, UMR_T9406, Laboratoire de Biomécanique et Mécanique des Chocs, F-69675, Bron*

‡ *Aalborg University, DK-9220, Aalborg, Denmark*

\\ *Université de Montréal, Montréal (Qc), Canada; Centre de Recherche de l'Hôpital Sainte-Justine, Montréal (Qc), Canada*

**Abstract**

Human movement analysis is frequently accomplished through multibody kinematic optimisation which enforces joint constraints between adjacent segments. Despite the popularity of the approach, an array of different joint models have been applied in the literature which is known to affect the model-derived kinematics. The purpose of this study was to perform a literature review to determine the different joint models used when applying multibody kinematic optimisation to the full body, upper and lower limbs.
Embase, Medline, Scopus, PubMed, and Web of Science were systematically searched and a total of 66 relevant articles were identified and included in the review.
The main finding was that the upper and lower limb joints were typically modelled as spherical, revolute or universal joints with the purpose of removing non-physiological joint dislocation effects due to soft tissue artefact that would otherwise be predicted with single-body optimisation. A diversity of joint models used in multibody kinematic optimisation was found in the literature. The most frequently used models were the simple, idealised models which, however, have also been criticised for not accurately replicating the detailed joint mechanics. On the other hand, more advanced joint models have emerged, such as parallel mechanisms or coupling equations between the joint degrees of freedom. Nevertheless, no consensus exists on how the joints should be defined to accurately estimate the overall joint kinematics with multibody kinematic optimisation.
The review also revealed that the method has also been referred to under other names such as 'global optimisation' and 'inverse kinematics', which can be misleading since these names also have other, and more accepted, meanings. The authors, therefore, recommend that, in the future, the process is termed multibody kinematic optimisation.

*Keywords: least-squares optimisation, state-of-the-art, kinematic models*

## 1. Introduction

Multibody kinematic optimisation is increasingly used to determine human joint kinematics from motion analysis systems (*e.g.*, stereo-photogrammetry or inertial sensors) by accounting for joint characteristics. The method is alternatively called 'global optimisation', 'inverse kinematics' or 'motion reconstruction' in different research fields. While commonly used methods (*e.g.*, marker-cluster least-squares matching also referred to as single-body optimisation) consider each segment independently, multibody kinematic optimisation determines the pose of all the segments attached by various joints in the same process. The general principle is typically to minimise, in least-squares sense, the difference between measured and model-determined trajectories of skin markers subject to rigid body and kinematic constraints.
Multibody kinematic optimisation is a key step in musculoskeletal modelling and is commonly used for kinematic and dynamic analysis with the aim of compensating for the soft tissue artefact and avoid apparent joint dislocations found when using single-body optimisation.
The model-derived kinematics largely depends on the definition of the joint models. In this study, a literature review was performed in order to determine the different joint models used in

*Corresponding author. Email: raphael.dumas@ifsttar.fr

multibody kinematic optimisation when applied to the full body, upper or lower limbs.

## 2. Materials and Methods

### *2.1. Search strategy*

An electronic search was performed (in January 2016) in Embase, Medline, Scopus, PubMed, and Web of Science. Logical expressions for the search included 'optim* or kalman', 'kinemat* joint', 'subject or human or limb', and 'model* or over*determ*'. The search was based on the title, keywords and abstract. Reference list of key studies were also cross-referenced to obtain further articles. The articles retrieved from the search strategy were reviewed according to the following exclusion criteria: no English language, conference proceeding, single body or under-constrained optimisation, no kinematics results reported, predictive simulation, markerless, sensorless or single-camera motion analysis, application in cadaveric specimens, animal, robots and machines. Studies focussing on spine, hand, foot and mandible were also excluded.

### *2.2. Data extraction*

The definition of the joint models were extracted from the reviewed articles. The joint models were classified in four categories:

- U (universal),
- H (hinge),
- S (spherical),
- C (joint models that defined closed loops and coupling relations between the joint degrees of freedom).

In this last category and in other miscellaneous cases, the definition of the joint models was detailed.

## 3. Results

### *3.1. Search yield*

The search results were Embase: 738, Medline: 729, Scopus: 721, PubMed: 169, Web of Science: 417. After removing duplicates, the number of articles was 1441. According to the exclusion criteria, 55 articles were selected from the search, 8 more articles were obtained by cross-referencing and 4 very recent articles known by the authors were finally added for a total of 66 articles.

### *3.2. Upper limb joint models*

Table 1 summarizes the type of joints found in the literature to model the upper limb. The most current open-loop upper limb kinematic chains included universal sterno-clavicular, elbow and wrist joints and a spherical scapulo-humeral joint (Prokopenko et al. 2001; Cerveri et al. 2003; Pontonnier and Dumont 2009; Debril et al. 2011; Fohanno et al. 2013). In this case, no acromio-clavicular joint was modelled, only a clavicle segment links thorax and humerus.

Table 1: Occurrences of joint models used for wrist, elbow, thoraco-humeral (TH) or scapulo-humeral (SH), acromio-clavicular (AC), sterno-clavicular (SC) and scapuloa-thoracic joints.

| | Wrist | Elbow | TH or SH | AC | SC | ST |
|---|---|---|---|---|---|---|
| H | 0 | 5 | 0 | 0 | 0 | 0 |
| U | **9** | **13** | 1 | 0 | 5 | 0 |
| S | 6 | 5 | **17** | **5** | **6** | 0 |
| C | 0 | 0 | 2 | 0 | 0 | **5** |

Note: for each joint the value in bold corresponds to the most common model.

Alternatively, sterno-clavicular and acromio-clavicular joints were modelled as spherical (Jackson et al. 2012; Charbonnier et al. 2014; Laitenberger et al. 2015). Elbow and wrist joints were modelled as hinge and spherical, respectively (Cerveri et al. 2003; Ayusawa et al. 2014) or spherical (Roux et al. 2002; Lee et al. 2010; Sholukha et al. 2013).
Additionally, to allow for gleno-humeral translations, two studies considered six degrees of freedom (Roux et al. 2002; van den Bogert et al. 2013) while another considered 'soft constraints', that is to say that the spherical joint is modelled with a penalty-based method (Charbonnier et al. 2014).
Conversely, closed loops with thoraco-scapular (point(s)-on-ellipsoid) joint (Bolsterlee et al. 2014; Prinold and Bull 2014; El Habachi et al. 2015), and with humero-radial (spherical), humero-ulnar (linear annular) and radio-ulnar (spherical) joints (Laitenberger et al. 2015) were also proposed.
Other joint models relied on the definition of coupling equations between the degrees of freedom, especially scapular and clavicular rhythms (Sholukha et al. 2013; Seth et al. 2016).

### *3.3. Lower limb joint models*

Table 2 summarises the type of joints found in the literature to model the lower limb. The most current lower limb kinematic chains included spherical hip, hinge knee and universal ankle joints (Reinbolt et al. 2005; Reinbolt et al. 2007; Andersen et al. 2009; Andersen et al. 2010; Duprey et al. 2010; van den Bogert et al. 2013; Aguiar et al. 2014; Fohanno et al. 2014; Aguiar et al. 2015; Marra et al. 2015; Martelli et al. 2015; Myers et al. 2015). The universal joint at the ankle was either modelled as concurrent or non-concurrent axes to account for both talocrural and subtalar joints.
Alternatively, spherical hip, knee and ankle joints have been also widely used in multibody kinematic optimisation (Lu and O'Connor 1999; Charlton et al. 2004; Stagni et al. 2009; Duprey et al. 2010; Lee et al. 2010; Groen et al. 2012; Moniz-Pereira et al.

2014; Ojeda et al. 2014; Robinson et al. 2014; Aguiar et al. 2015; Clément et al. 2015). Therefore, only the translations were constrained.

Table 2: Occurrences of joint models used for hip, knee and ankle.

| | Ankle | Knee | Hip |
|---|---|---|---|
| H | 5 | **22** | 1 |
| U | **19** | 1 | 0 |
| S | 14 | 15 | **39** |
| C | 6 | 18 | 0 |

Note: for each joint the value in bold corresponds to the most common model.

Closed loops (*i.e.*, parallel mechanisms or four-bar mechanisms) were also proposed for the knee (Duprey et al. 2010; Clément et al. 2015; El Habachi et al. 2015; Gasparutto et al. 2015; Valente et al. 2015) and ankle joints (Duprey et al. 2010; El Habachi et al. 2015; Valente et al. 2015).

In the same way as for the upper limb, other knee (Sholukha et al. 2006; De Groote et al. 2008; Scheys et al. 2011; Li et al. 2012; Sholukha et al. 2013; Zheng et al. 2014; Bonnechère et al. 2015; Gasparutto et al. 2015; Martelli et al. 2015; Valente et al. 2015) and ankle joint models (Sholukha et al. 2006; Sholukha et al. 2013; Bonnechère et al. 2015) relied on the definition of coupling equations between the degrees of freedom. Additionally, 'soft constraints' that defined deformable ligaments with a penalty-based method were also proposed (Clément et al. 2015; Gasparutto et al. 2015) and a fully deformable knee joint was introduced using a 'force-dependent kinematics' method (Marra et al. 2015).

## 4. Discussion

The objective of the present study was to inventory the current joint models used in multibody kinematic optimisation for the estimation of the skeleton and/or joint kinematics. The main findings were that upper and lower limb joints were often modelled as hinge, universal or spherical joint with the main purpose of avoiding apparent joint dislocations as found when using single-body optimisation.

When joint displacements were of interest, the joints were modelled with three different approaches. First, 'soft constraints' were implemented using a penalty-based method (Charbonnier et al. 2014; Clément et al. 2015; Gasparutto et al. 2015). In this approach, a weighted sum of the squared distances between measured and model-determined skin marker trajectories and of the joint dislocations were minimised. The efficiency of the method relies on the choice of the weights. The 'force-dependent kinematics' method can be seen as an extension of the 'soft constraints' approach with contact and ligament stiffness instead of the numerical weights (Marra et al. 2015). Second, coupling equations between the degrees of freedom, and in particular between joint translations and rotations, were defined (Sholukha et al. 2006; Sholukha et al. 2013; Seth et al. 2016). The coupling equations were established on cadaver experiments and the consistency with the *in vivo* weight-bearing joint performance remains questioning. For instance, when personalised with bi-planar fluoroscopic data during gait, the coupling equations appeared largely altered at the knee (Zheng et al. 2014). Third, closed loops with simple joints in parallel (*e.g.*, sphere-on-plane contact, point-on-ellipsoid contact, isometric ligament) were proposed (Duprey et al. 2010; Bolsterlee et al. 2014; Prinold and Bull 2014; El Habachi et al. 2015; Valente et al. 2015). The bio-fidelity of such model is to be further validated but this approach has the advantage to be possibility personalised through more conventional medical imaging than fluoroscopy (Clément et al. 2015).

The main limitations of this study are that *i)* the quality of the papers was not assessed and *ii)* that some articles may not be found despite caution in the search. Indeed, the keywords for the search were general since a series of too specific words in pilot searches failed to find the most relevant articles already known by the authors. No keyword was introduced specific to the 'joint models' because this study is part of a larger systematic review.

As stated in the introduction, several expressions refer to multibody kinematic optimisation for the estimation of human kinematics when the optimisation problem is over-determined. 'Global optimisation' firstly introduced by Lu and O'Connor (1999) also refers to mathematical methods, including stochastic methods and metaheuristics, for finding global optimum. 'Inverse kinematics' more generally includes under-determined problems often found in computer animation to generate realistic poses and movements with limited information (*e.g.*, end effector position). To better follow in the future the development and results of such methods, the authors would like to recommend using the formal expression 'multibody kinematic optimisation'.

## 5. Conclusion

In conclusion, this literature review revealed that the upper and lower limb joints were often modelled as spherical, hinge or universal even though these fail to estimate joint displacements that are present in some of the non-conforming joints of the human body. When joint displacement estimates were desired, multiple joint models have been proposed but, at this point, there does not appear to be a consensus in the literature of how this is best accomplished.

Finally, several expressions for multibody kinematic optimisation were found, and the authors encourage the community to adapt a consistent vocabulary to avoid confusion with other well-established names in other fields as since such as ‘global optimisation’ and ‘inverse kinematics’.

## References


Aguiar L, Andrade C, Branco M, Santos-Rocha R, Vieira F and Veloso A, 2015. Global Optimization Method Applied to the Kinematics of Gait in Pregnant Women. Journal of Mechanics in Medicine and Biology In press: 1650084.

Aguiar L, Santos-Rocha R, Branco M, Vieira F and Veloso A, 2014. Biomechanical Model for Kinetic and Kinematic Description of Gait During Second Trimester of Pregnancy to Study the Effects of Biomechanical Load on the musculoskeletal system. Journal of Mechanics in Medicine and Biology 14(1): 1450004.

Andersen MS, Benoit DL, Damsgaard M, Ramsey DK and Rasmussen J, 2010. Do kinematic models reduce the effects of soft tissue artefacts in skin marker-based motion analysis? An in vivo study of knee kinematics. Journal of Biomechanics 43(2): 268-273.

Andersen MS, Damsgaard M and Rasmussen J, 2009. Kinematic analysis of over-determinate biomechanical systems. Computer Methods in Biomechanics and Biomedical Engineering 12(4): 371-384.

Ayusawa K, Ikegami Y and Nakamura Y, 2014. Simultaneous global inverse kinematics and geometric parameter identification of human skeletal model from motion capture data. Mechanism and Machine Theory 74: 274-284.

Bolsterlee B, Veeger HEJ and van der Helm FCT, 2014. Modelling clavicular and scapular kinematics: from measurement to simulation. Medical & Biological Engineering & Computing 52(3): 283-291.

Bonnechère B, Sholukha V, Salvia P, Rooze M and Van Sint Jan S, 2015. Physiologically corrected coupled motion during gait analysis using a model-based approach. Gait & Posture 41(1): 319-322.

Cerveri P, Pedotti A and Ferrigno G, 2003. Robust recovery of human motion from video using Kalman filters and virtual humans. Human movement science 22(3): 377-404.

Cerveri P, Rabuffetti M, Pedotti A and Ferrigno G, 2003. Real-time human motion estimation using biomechanical models and non-linear state-space filters. Medical & Biological Engineering & Computing 41(2): 109-123.

Charbonnier C, Chagué S, Kolo FC, Chow JCK and Lädermann A, 2014. A patient-specific measurement technique to model shoulder joint kinematics. Orthopaedics & Traumatology: Surgery & Research 100(7): 715-719.

Charlton IW, Tate P, Smyth P and Roren L, 2004. Repeatability of an optimised lower body model. Gait & Posture 20(2): 213-221.

Clément J, Dumas R, Hagemeister N and de Guise JA, 2015. Soft tissue artifact compensation in knee kinematics by multi-body optimization: Performance of subject-specific knee joint models. Journal of Biomechanics 48(14): 3796-3802.

De Groote F, De Laet T, Jonkers I and De Schutter J, 2008. Kalman smoothing improves the estimation of joint kinematics and kinetics in marker-based human gait analysis. Journal of biomechanics 41(16): 3390-3398.

Debril J-F, Pudlo P, Simoneau E, Gorce P and Lepoutre FX, 2011. A method for calculating the joint coordinates of paraplegic subjects during the transfer movement despite the loss of reflective markers. International Journal of Industrial Ergonomics 41(2): 153-166.

Duprey S, Cheze L and Dumas R, 2010. Influence of joint constraints on lower limb kinematics estimation from skin markers using global optimization. Journal of Biomechanics 43(14): 2858-2862.

El Habachi A, Duprey S, Cheze L and Dumas R, 2015. A parallel mechanism of the shoulder-application to multi-body optimisation. Multibody System Dynamics 33(4): 439-451.

El Habachi A, Moissenet F, Duprey S, Cheze L and Dumas R, 2015. Global sensitivity analysis of the joint kinematics during gait to the parameters of a lower limb multi-body model. Medical & Biological Engineering & Computing 53(7): 655-667.

Fohanno V, Begon M, Lacouture P and Colloud F, 2014. Estimating joint kinematics of a whole body chain model with closed-loop constraints. Multibody System Dynamics 31(4): 433-449.

Fohanno V, Lacouture P and Colloud F, 2013. Improvement of upper extremity kinematics estimation using a subject-specific forearm model implemented in a kinematic chain. Journal of Biomechanics 46(6): 1053-1059.

Gasparutto X, Sancisi N, Jacquelin E, Parenti-Castelli V and Dumas R, 2015. Validation of a multi-body optimization with knee kinematic models including ligament constraints. Journal of Biomechanics 48(6): 1141-1146.

Groen BE, Geurts M, Nienhuis B and Duysens J, 2012. Sensitivity of the OLGA and VCM models to erroneous marker placement: effects on 3D-gait kinematics. Gait & Posture 35(3): 517-521.

Jackson M, Michaud B, Tetreault P and Begon M, 2012. Improvements in measuring shoulder joint kinematics. Journal of Biomechanics 45(12): 2180-2183.

Laitenberger M, Raison M, Perie D and Begon M, 2015. Refinement of the upper limb joint kinematics and dynamics using a subject-specific closed-loop forearm model. Multibody System Dynamics 33(4): 413-438.

Lee J, Flashner H and McNitt-Gray JL, 2010. Estimation of Multibody Kinematics Using Position Measurements. Journal of Computational and Nonlinear Dynamics 6(3): 031001.

Li K, Zheng L, Tashman S and Zhang X, 2012. The inaccuracy of surface-measured model-derived

tibiofemoral kinematics. Journal of Biomechanics 45(15): 2719-2723.
Lu TW and O'Connor JJ, 1999. Bone position estimation from skin marker co-ordinates using global optimisataion with joint constraints. Journal of Biomechanics 32(2): 129-134.
Marra MA, Vanheule V, Fluit R, Koopman BHFJM, Rasmussen J, Verdonschot N and Andersen MS, 2015. A Subject-Specific Musculoskeletal Modeling Framework to Predict In Vivo Mechanics of Total Knee Arthroplasty. Journal of Biomechanical Engineering 137(2): 020904.
Martelli S, Kersh ME and Pandy MG, 2015. Sensitivity of femoral strain calculations to anatomical scaling errors in musculoskeletal models of movement. Journal of Biomechanics 48(13): 3606-3615.
Martelli S, Valente G, Viceconti M and Taddei F, 2015. Sensitivity of a subject-specific musculoskeletal model to the uncertainties on the joint axes location. Computer Methods in Biomechanics and Biomedical Engineering 18(14): 1555-1563.
Moniz-Pereira V, Cabral S, Carnide F and Veloso AP, 2014. Sensitivity of joint kinematics and kinetics to different pose estimation algorithms and joint constraints in the elderly. Journal of Applied Biomechanics 30(3): 446-460.
Myers CA, Laz PJ, Shelburne KB and Davidson BS, 2015. A Probabilistic Approach to Quantify the Impact of Uncertainty Propagation in Musculoskeletal Simulations. Annals of Biomedical Engineering 43(5): 1098-1111.
Ojeda J, Martinez-Reina J and Mayo J, 2014. A method to evaluate human skeletal models using marker residuals and global optimization. Mechanism and Machine Theory 73: 259-272.
Pontonnier C and Dumont G, 2009. Inverse dynamics method using optimization techniques for the estimation of muscles forces involved in the elbow motion. International Journal on Interactive Design and Manufacturing 3(4): 227-236.
Prinold JAI and Bull AMJ, 2014. Scaling and kinematics optimisation of the scapula and thorax in upper limb musculoskeletal models. Journal of Biomechanics 47(11): 2813-2819.
Prokopenko RA, Frolov AA, Biryukova EV and Roby-Brami A, 2001. Assessment of the accuracy of a human arm model with seven degrees of freedom. Journal of Biomechanics 34(2): 177-185.
Reinbolt JA, Haftka RT, Chmielewski TL and Fregly BJ, 2007. Are patient-specific joint and inertial parameters necessary for accurate inverse dynamics analyses of gait? IEEE Transactions on Biomedical Engineering 54(5): 782-793.
Reinbolt JA, Schutte JF, Fregly BJ, Koh B, Haftka RT, George AD and Mitchell KH, 2005. Determination of patient-specific multi-joint kinematic models through two-level optimization. Journal of Biomechanics 38(3): 621-626.
Robinson MA, Donnelly CJ, Tsao J and Vanrenterghem J, 2014. Impact of Knee Modeling Approach on Indicators and Classification of Anterior Cruciate Ligament Injury Risk. Medicine & Science in Sports & Exercise 46(7): 1269-1276.
Roux E, Bouilland S, Godillon-Maquinghen AP and Bouttens D, 2002. Evaluation of the global optimisation method within the upper limb kinematics analysis. Journal of Biomechanics 35(9): 1279-1283.
Scheys L, Desloovere K, Spaepen A, Suetens P and Jonkers I, 2011. Calculating gait kinematics using MR-based kinematic models. Gait & Posture 33(2): 158-164.
Seth A, Matias R, Veloso AP and Delp SL, 2016. A Biomechanical Model of the Scapulothoracic Joint to Accurately Capture Scapular Kinematics during Shoulder Movements. PLoS One 11(1): e0141028.
Sholukha V, Bonnechere B, Salvia P, Moiseev F, Rooze M and Jan SVS, 2013. Model-based approach for human kinematics reconstruction from markerless and marker-based motion analysis systems. Journal of Biomechanics 46(14): 2363-2371.
Sholukha V, Leardini A, Salvia P, Rooze M and Van Sint Jan S, 2006. Double-step registration of in vivo stereophotogrammetry with both in vitro 6-DOFs electrogoniometry and CT medical imaging. Journal of Biomechanics 39(11): 2087-2095.
Stagni R, Fantozzi S and Cappello A, 2009. Double calibration vs. global optimisation: performance and effectiveness for clinical application. Gait & Posture 29(1): 119-122.
Valente G, Pitto L, Stagni R and Taddei F, 2015. Effect of lower-limb joint models on subject-specific musculoskeletal models and simulations of daily motor activities. Journal of Biomechanics 48(16): 4198-4205.
van den Bogert AJ, Geijtenbeek T, Even-Zohar O, Steenbrink F and Hardin EC, 2013. A real-time system for biomechanical analysis of human movement and muscle function. Medical & Biological Engineering & Computing 51(10): 1069-1077.
Zheng L, Li K, Shetye S and Zhang X, 2014. Integrating dynamic stereo-radiography and surface-based motion data for subject-specific musculoskeletal dynamic modeling. Journal of Biomechanics 47(12): 3217-3221.